

## **From Disturbances to Instabilities, to Breakdown to Turbulence: the Physics of Transition in Boundary Layers**

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In order to understand the end-stages of boundary layer transition in low as well as high disturbance environments (including bypass transition) it is desirable to establish a unified view of the sequences of physico-mathematical phenomena that lead from laminar flow to self-sustained "bursting" in wall turbulence. The dominant driving disturbances: oncoming free turbulence, unsteady pressure fields (including sound), inhomogeneous density fields, inhomogeneities in wall geometry (including distributed roughness) etc., all force disturbed motions within the boundary layer via multiple competitive receptivity mechanisms. For small disturbances, a sequence of (often linearizable) instabilities then leads to sporadic local bursting very near the wall which can sustain turbulence. The local seeds of turbulence then somehow propagate (as in case of idealized Emmons' spots) to engulf quite rapidly the surrounding disturbed but still laminar regions. The instability sequences differ with basic parameters and with the nature of internalized ("received") boundary-layer disturbances, thus providing highly non-unique roads to turbulence. There may be fewer modes of the final onset of bursting, the criteria for which are not yet clear.

For larger disturbances (even more non-unique) the instabilities will generally bypass the linearizable primary amplified modes (T.S. waves, steady and unsteady cross flow modes, Goertler modes) and amplify nonlinearly and "inviscidly", roughly starting with the secondary instability phenomena. Special attention is called to "algebraically" growing instabilities, which theoretically can grow from rather small disturbances, but must be "environmentally realizable". The final "bursting" breakdown process is likely to be similar to that for the non-bypass cases. In both small and large disturbance cases, the number of governing parameters is large, ten to twenty or more.

In prediction of transition and in modeling of its end stages, idealization and simplification is unavoidable. The purpose of this lecture is to establish a common vocabulary for the various processes and their dominant mechanisms. Then we should be able to compare various theoretic-empirical methods, both in terms of the success in correlating (limited) data and in terms of the essential physics retained in the idealizations (as a guide to its generality).



# END STAGES of TRANSITION

Could be for either

LOW-DISTURBANCE ROAD  
involving HIGHER INSTABILITIES

or

BYPASSES with STRONG (S) DISTURBANCES  
WEAK - (W)

DEFINITELY NON-LINEAR (non-superposable, NON-UNIQUE)

∴ information primarily from

EXPERIMENTS  
Direct Numer. Soln

• PARTICULAR SOLUTIONS

INCREDIBLY RICH PATTERNS  
OF BEHAVIOR

GOVERNED by  
In. Cond + Bound C.

CONCEPTUAL GENERALIZATIONS?

via CLASSIFICATIONS

of distinguishable  
MECHANISMS

of functional  
CLASSES of DISTURBANCES  
I.C. and B.C.

PRIMARY PARAMETERS

(NON LINEARITY → CHANGES IN THE BASE FLOW)  
• THRESHOLDS

AMPLITUDE - DEPENDENT  
CHANGES OF FIELDS on  
the ROADS to TURBULENCE

FOR APPLICATIONS  
SIMPLIFICATIONS AND IDEALIZATIONS  
ARE UNAVOIDABLE

CONSISTENCY OF "PHYSICS"

"GUARDIAN of Reliability and  
concept generality

illustration:

role of EMMONS' SPOTS  
in highly disturbed environments

illustration:

FINAL BREAKDOWN

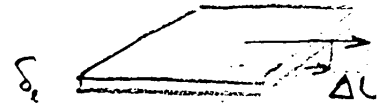
Initiation of  
self-sustained BURSTING

→ IS LOCAL, SPORADIC, probably caused  
by EXTREMA of DISTURBANCES

CAN IT BE CORRELATED BY A SINGLE  
AVERAGE MEASURE : % Tu ?

(S<sub>1</sub>)

SYSTEMS APPROACH TO  
TRANSITION  
from



Thin, finite  $\delta_{lam}$  SLABS or SHEATHS

with LAMINAR VORTICITY  $\vec{\Omega}(y)$  DISTRIBUTION

at lower  $Re \sim \frac{\Delta U_{\infty} \delta_e}{\nu}$  QUASI-2D, QUASI STEADY

streamwise  $L_x \gg \delta_{lam}$   
spanwise  $L_y$

BL's (MIXING L's, JETS, WAKES, etc)

SUBJECTED TO ENVIRONMENTAL

weak  $|\Delta \vec{v}| \ll \Delta U_{\infty}$  Free-stream AND Boundary

NONHOMOGENEITIES  
in  $x, z, t$

disturbances with characteristi

longer scales and times

(except for ROUGHNESS)

INEVITABLY  
AS  $Re \uparrow$

to

SCALE  
DISCREPANCIES

finite  $\delta_{tu}$  SLABS or COLUMNS

with TURBULENT VORTICITY  $\vec{\Omega}(x, y, z, t)$   
DISTRIBUTIONS

with space-time DISORDER (chaos)

(A) with "large coherent eddies"  $L_z \sim \delta_{tu}$   
 $L_x \sim 3\delta_{tu}$

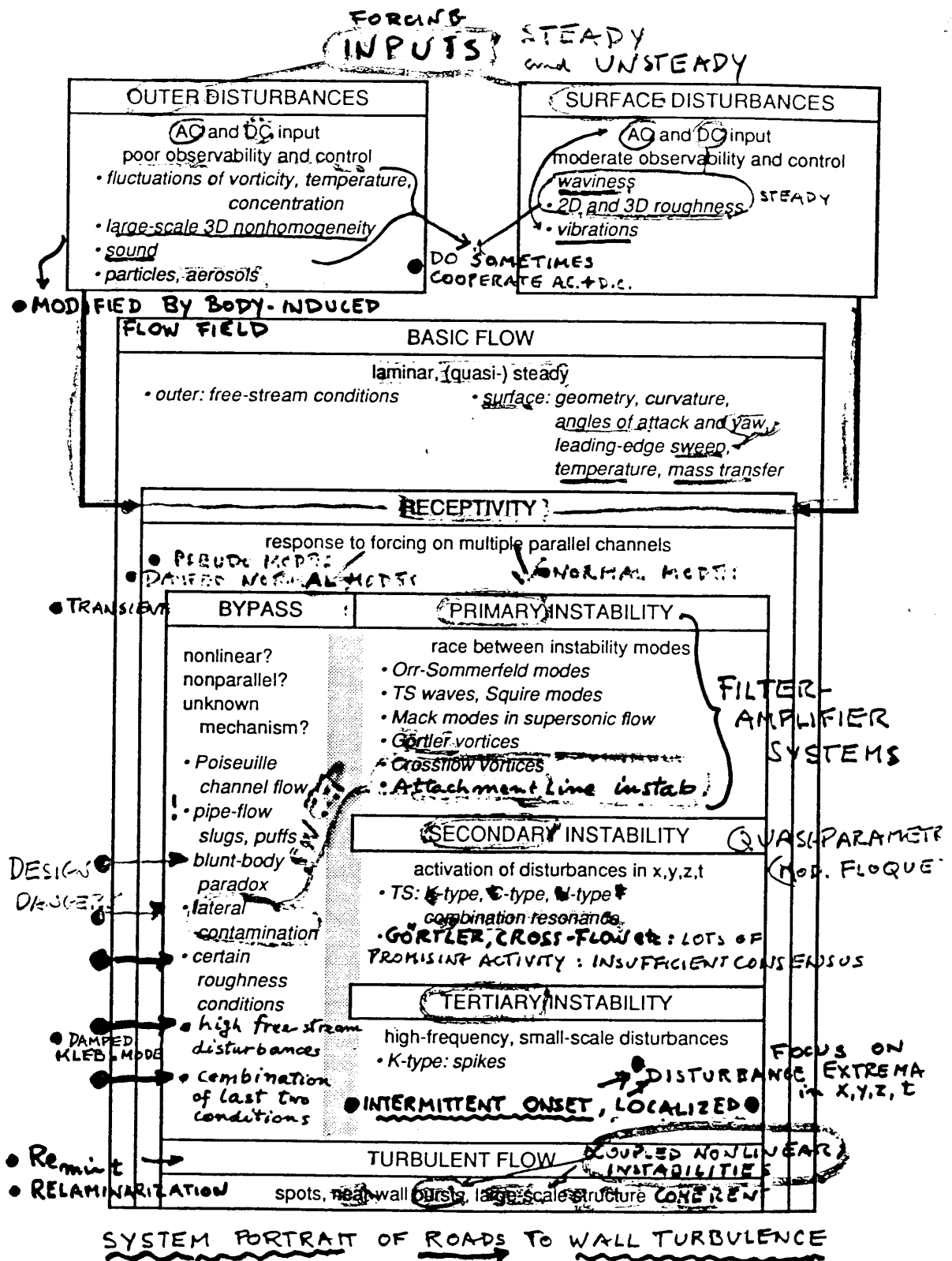
(B) with fine wall-scaled,  $l^+ \sim 100 \ll \delta_{tu}$ , NONLINEAR  
INSTABILITY with a threshold,

referred to as BURSTING for SHORT

(Killed in  
relaminari-  
zation!)

See S.K. ROBINSON 1991 Ann. Rev. Fluid Mech. •  $Re_{crit}$

STRONG  
with  $z$  asymmetry

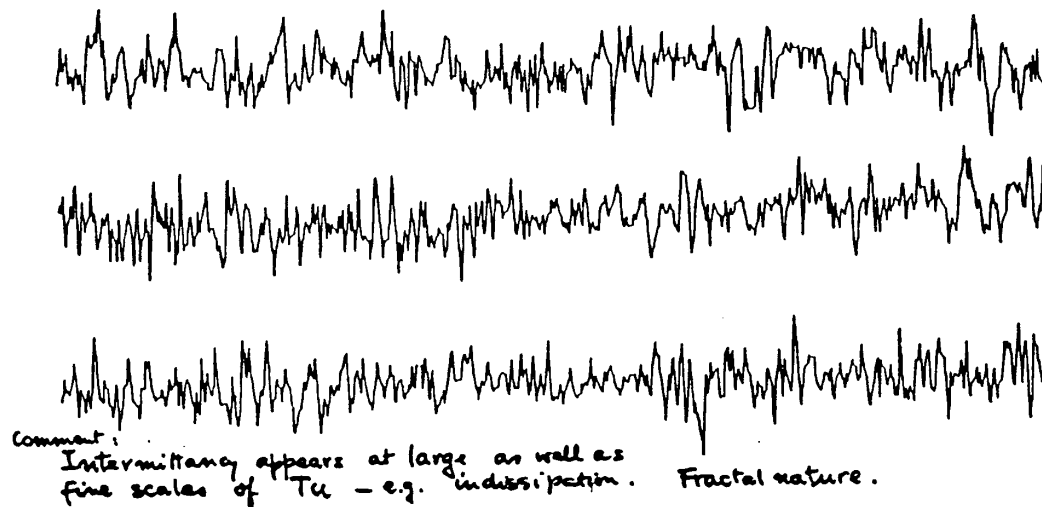


J. KENDALL '92

# FREESTREAM FLUCTUATION RECORDS

0.65 SEC DURATION EACH  
 $u'/U_0 = 0.22\%$

STATIONARY INPUT



YET DISCRETE OUTPUT

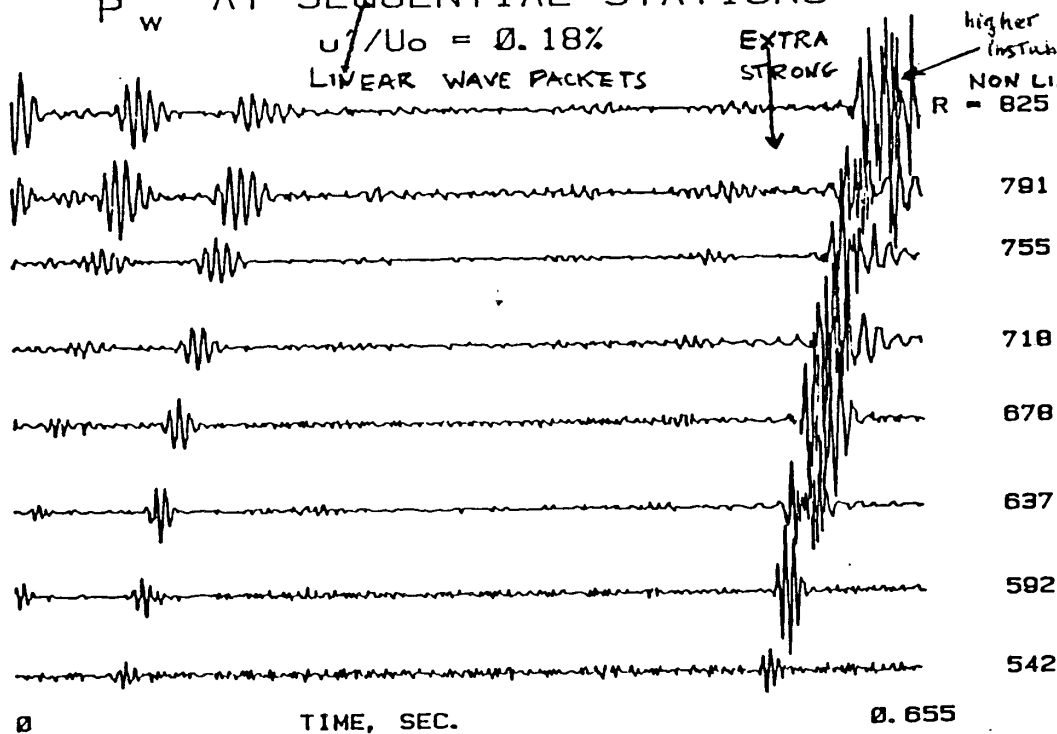
$P'_w$  AT SEQUENTIAL STATIONS

$u'/U_0 = 0.18\%$

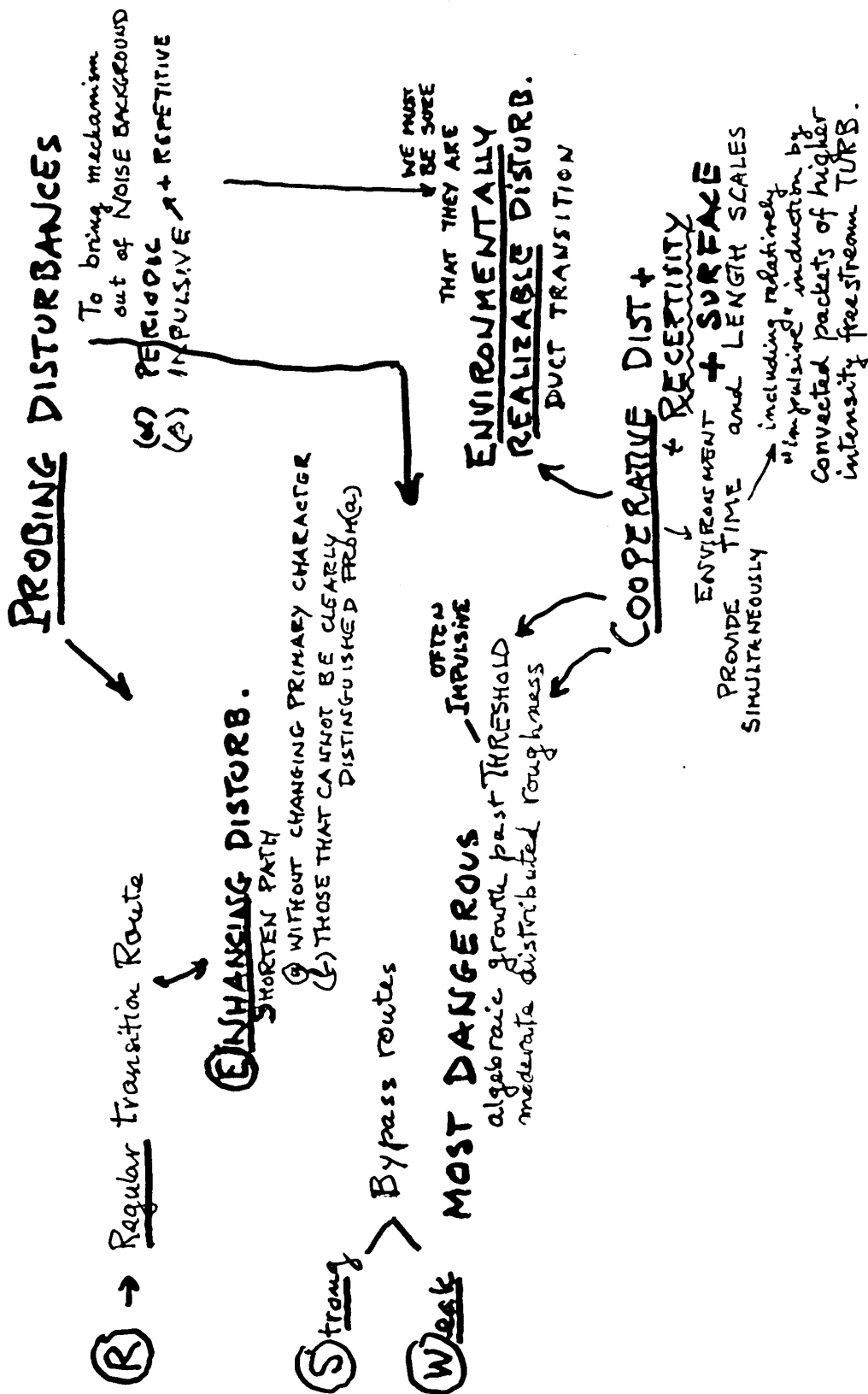
LINEAR WAVE PACKETS

EXTRA  
STRONG

higher  
instability  
NON LINEAR!!  
 $R = 825$



# FUNCTIONALITY OF DISTURBANCE CLASSES



ROUGHNESS CAN FUNCTION IN ALL THESE CATEGORIES  
BUT BEWARE OF —

## TRANSIENT DISTURBANCES

- can lead to substantial "algebraic" growth even when <sup>disturbances</sup> are
- (W) Weak - a property of nonsymmetric PDE operators (for which eigenfunctions are not independent = non normal e.g. Schmid, Henningson, Khorrami & Malik: "A study of eigenvalue sensitivity for hydrodynamic stability operators", Theor. & Comp. Fluid Dyn (in Press 1993). In a system with damped eigenmodes, the growth may be sufficient (before ultimate decay) to modify the system nonlinearly and lead to a bypass (as observed experimentally for most duct and plane Couette flows) For Stronger disturbances this road to turbulence may be competitive with "REGULAR" paths, based on amplified eigenfunctions and higher-order instabilities.
  - (S)

Obviously, the (W) category represents the larger danger in design. ON THE OTHER HAND, these disturbances are ARTIFICIAL and question remains whether and how they can be actually induced by a given DISTURBANCE ENVIRONMENT

ONLY THE CLASS OF ENVIRONMENTALLY REALIZABLE DISTURBANCES is practically relevant. HOWEVER, conceptually it is important to understand the mechanisms - they can even be used as TRIPPERS.

Groups at MIT: Landahl, Breuer, Henningson, Reddy, using Schmid (Gustafson of Swedish KTH) and Lehigh Univ. Charles Smith, Haji-Haidari, J.D.A. Walker, B. Taylor etc. have done both experimental and theoretical work. Butler, K. and Farrell, B (1992): "3-dimensional optimal perturbations in viscous flows" Phys. Fl. A, 4(8) used variational theory to find alg. growing flows undoubtedly related to "Klebanoff damped modes" < Recr.

L. TREFETHEN'S PSEUDO MODES for NON-NORMAL OPERATORS (Book forthcoming) applied to linearized Navier-Stokes eqs forced by  $e^{-i\omega t} v(x, y, z)$  imposed at every point in the shear layer. The response is gauged in terms the resolvent matrix of the system. Its norm  $\rightarrow \infty$  for  $v$ -eigen solutions at  $\omega_{cr}$  and can be large for complex  $\omega$  near  $\omega_{cr}$ . When  $\omega_{cr}$  is slightly damped ( $\text{Im}(\omega)$  just below zero) mode responses with  $\omega$  near  $\omega_{cr}$  can be substantially amplified i.e. PSEUDO-RESONANT. The forcing functions  $v(x, y, z)e^{-i\omega t}$  would have to be induced by the environment. Which of these are environmentally realizable?



J.D. SWEARINGEN, U.So. Cal. Thesis 1985

smoke wire  $y_{sw}$  at  $x = 21.5 \text{ cm}$ .

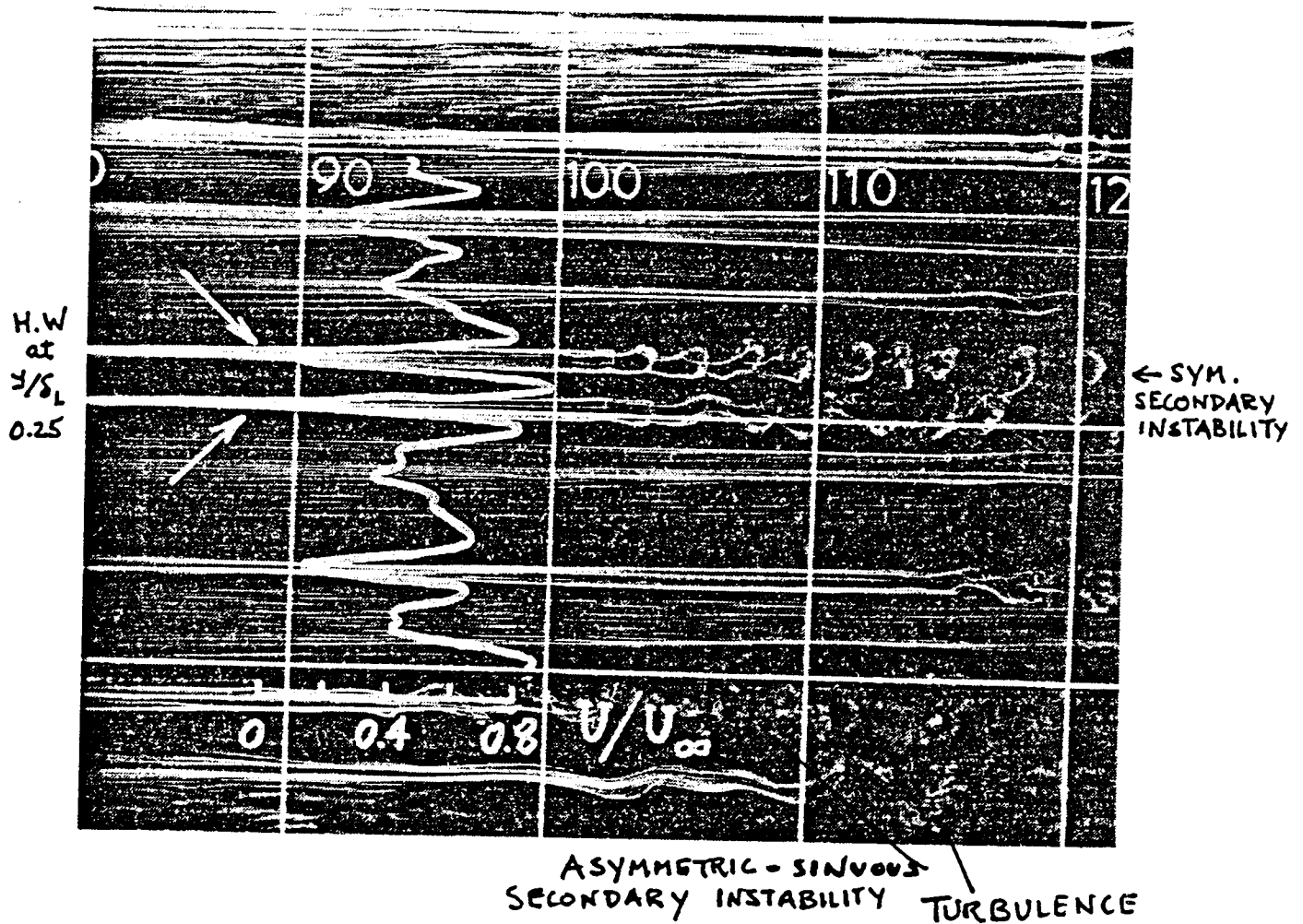
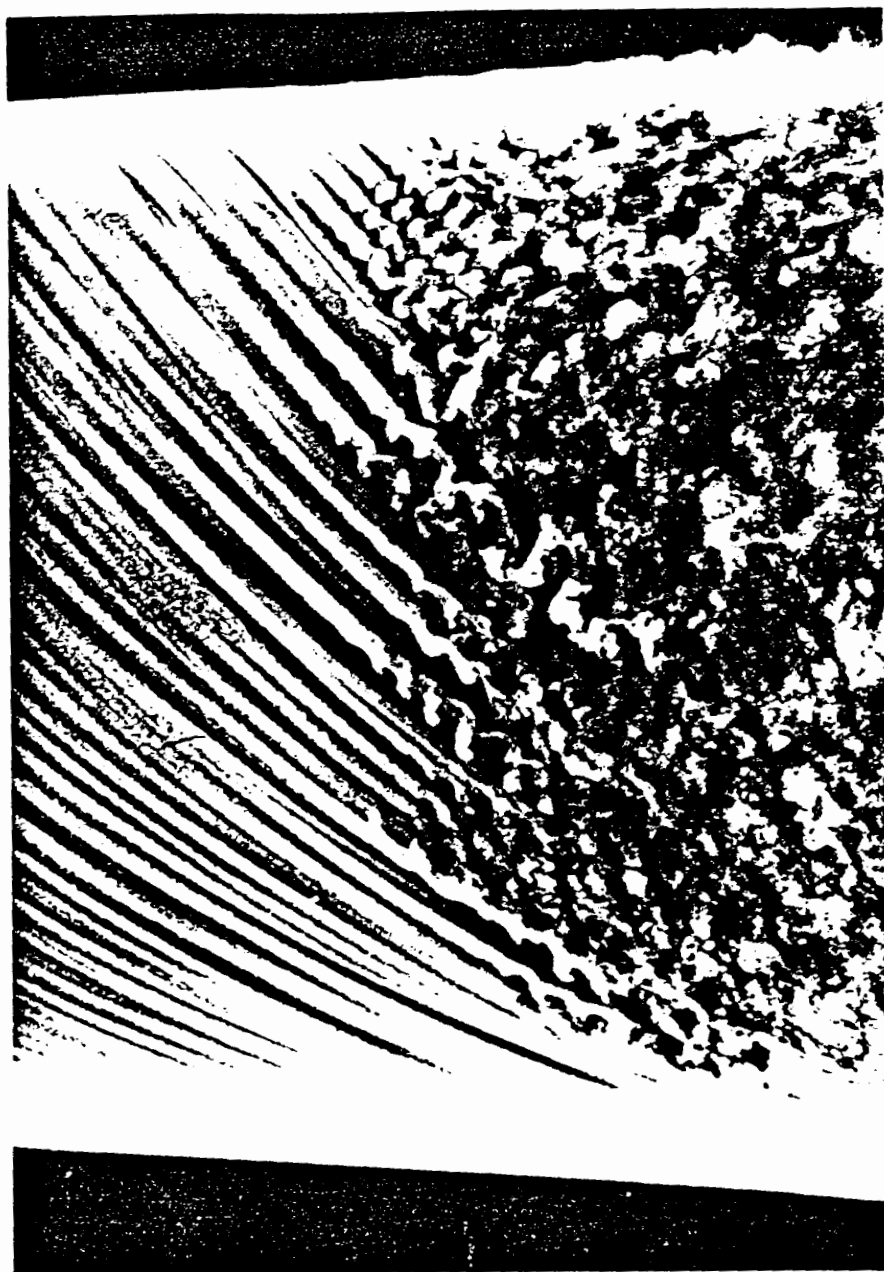


Figure 4.3: Spanwise variation of the mean streamwise velocity at  $y/\delta_L = 0.25$  superimposed on the flow visualization of figure 4.2a.



J. KEGELMAN

Figure 65: Enlargement of Striations Illustrating Striation Breakdown ( $V_s/U_\infty = 0.825$ ,  $Re_L = 0.814 \times 10^6$ )

# WHAT IS FREE-STREAM TU that gives "NATURAL" TRANSITION?

Grid Tu  
Screen Tu  
Tu in any WTunnel  
Tu in Turbomachinery  
Tu in atmospheric flight

Even when nearly homogeneous and nearly isotropic (it) has unknown coherent structures and intermittencies ~ fractals.

masked by the one-dimensional time signals and spectra of hot wires

• Borm in separated shear layers;  
wakes fed by  $\overline{v_{tang} \cdot v_{nom}} \frac{\partial V_{tang}}{\partial n}$   
• decays in absence of mean flow grad  $\nabla$   
• and rejuvenates when comes on near stag regions in contractions over wings and blades

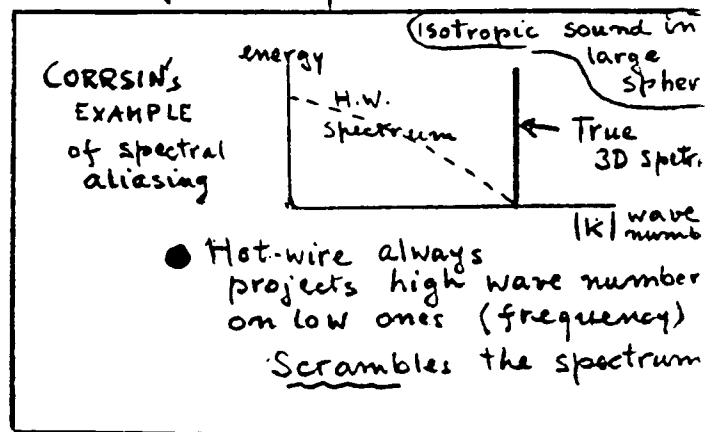
BÖTTCHER

• carry streamwise vorticity  $\Omega$   
(Klebanoff, Kottke)  
• direct feeding of Görtler instab. and cross flow Zieg instab.

To understand:

concentrate on the sporadic energetic extremal events

(possibly enhanced by "probing" periodic disturbances)



Then two-point space-time correlations in free stream  
one in f.s, one in BL.

Kendall ( ) showed that disturbances associated with the, slightly damped were moving towards the wall.

**KLEBANOFF MODE RESPONSE**

↓ dominated by low frequency. Streamwise vortices which generate large  $u'$  fluctuations (with theoretical low  $v'$  and  $w'$ )

Such disturbed motion then influences subsequent instabilities especially secondary instabilities

agreement with Butler and Farrell 1992 theory

